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# Insensitive Munitions/Surety Joint Munitions Program Five Year Plan for FY10-14

H. K. Springer

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## Insensitive Munitions/Surety

### Joint Munitions Program Five Year Plan for FY10-14

#### Background Information

Lawrence Livermore National Laboratory  
 H. Keo Springer, P. O. Box 808, Livermore, CA 94551  
 Tel (925) 424-6502, Fax (925) 424-3281, [springer12@llnl.gov](mailto:springer12@llnl.gov)  
 TCG-III

#### Customers

Jamie Neidert AMRDEC-Redstone Arsenal <a href="mailto:Jamie.Neidert@us.army.mil">Jamie.Neidert@us.army.mil</a>	Steven Collignon NSWC-Dahlgren <a href="mailto:steven.collignon@navy.mil">steven.collignon@navy.mil</a>	Jon Maienschein LLNL <a href="mailto:maienschein1@llnl.gov">maienschein1@llnl.gov</a>
Ernie Baker ARDEC-Picatinny Arsenal <a href="mailto:ernest.l.baker@us.army.mil">ernest.l.baker@us.army.mil</a>	David Lambert AFRL/Munitions-Eglin <a href="mailto:david.lambert@eglin.af.mil">david.lambert@eglin.af.mil</a>	Stan DeFisher ARDEC-Picatinny Arsenal <a href="mailto:stanley.defisher@us.army.mil">stanley.defisher@us.army.mil</a>

#### Project Goal

The overall goal of this project is to enable hazard assessment modeling of munition systems. During its life-cycle, munitions can be exposed to a variety of unplanned stimuli. Predictive modeling tools capable of determining munition response to these stimuli can reduce the costs associated with Insensitive Munitions (IM) design and qualification. These tools can be used to integrate IM compliance early into the design stages of new munition systems, reducing the costs associated with late-stage design modifications. These tools can also be used to assess the hazard response of existing munition systems, reducing the costs associated with IM qualification testing.

#### Project Objective

The objective of this project is to develop and validate models within the ALE3D framework for predicting the explosive violence resulting from thermal and mechanical insults. These models will account for energetic material type, thermal history, mechanical and thermal damage, and confinement conditions.

In thermal cookoff events, predictions of the ignition time and temperature, as well as explosive violence, are important to ensure the safe handling of energetic materials. Accurate predictions require codes that properly incorporate thermal transport, chemical decomposition, and mechanical deformation and fracture of the assembly. Thermal transport is required transfer heat from an external source to the energetic material. When the energetic material becomes hot enough, the material undergoes chemical transitions to different species while releasing or absorbing heat. Each species contains a unique equation of state that contributes to the total stress of the chemical mixture. This change in stress distribution causes mechanical deformation and fracture of the assembly, which can moderate the burn rate and overall explosive violence. The fragment size and velocity distribution serves as the violence metrics, or IM signatures, for any subsequent study.

The response of energetic materials to bullet and fragment impacts ranges from prompt shock to detonation transition (SDT), non-prompt unknown transition to detonation (XDT) (presently associated with the recompression of damaged energetic material), and non-prompt deflagration to detonation transition (DDT), to varying degrees of burning reactions. Since SDT models are relatively mature, the focus of this project is to develop models for the sub-detonative response of energetic materials. In doing so, many of the components needed for XDT and DDT modeling will be addressed. Accurate sub-detonative predictions require codes that properly incorporate the impact and burn-front damage mechanisms, non-prompt ignition, burning of damaged energetics, and mechanical deformation and fracture of the assembly. During bullet or fragment impact, the energetic material can be damaged in shear-compression and tension. Non-prompt ignition may occur due to surface frictional work, energetic grain fracture, or localized shear banding in the grain-binder system. The burning of damaged energetics is facilitated by the infiltration of shear damaged material by hot, high-pressure gasses. Above a critical pressure and temperature threshold, the infiltrated material ignites and burns. At higher pressures, the burn front, itself, can induce micro-fracture in the material and further enhance the burn rate. Under heavy confinement, pressure can significantly build-up and ramp-up to a detonation.

## Task Descriptions

### *Task 1: Impact response modeling (TRL-2/3)*

The objective of this task is to develop impact response models for energetic materials, implement them in ALE3D, validate them with sub-scale test data, and predict the hazard response of complex, integrated munition systems. Models will include impact-induced damage, ignition, flame-spread and deflagration in mechanically-damaged energetic materials, and the effects of confinement response.

The specific focus of this task will be to develop and validate non-prompt ignition models, impact damage models, and convective burn models in ALE3D for HMX-based explosives and high performance propellant (HPP). Non-prompt ignition and damage models will be based on solid mechanics principals and informed by the energetic material composition. The convective burn models will be based on the ALE3D multi-physics/multi-phase framework, integrating fragmentation, ignition, flame spread, and combustion into a single model. The application of these spirally-developed models to the bullet-fragment impact (BFI) of rocket motors and sub-detonative response of conventional munitions will be a key metric for success.

### *Task 2: Impact response experiments (TRL-2/3)*

The objective of this task is to perform impact response experiments on energetic materials, as part of developing new and validating existing impact response models. Experiments range from phenomenological exploration to routine testing for model calibration.

The near-term focus of this task will be to design and conduct sub-scale experiments that provide insight into the in-bore damage, ignition, and deflagration of HPP rocket motors subjected to bullet-fragment impact (BFI). These experiments will complement the burn to violent reaction

(BVR) experiments being conducted by AMRDEC. This testing will utilize advanced diagnostics and attempt to, where possible, transition diagnostics to DoD customers.

### *Task 3: Thermal response modeling (TRL-2/3)*

The objective of this task is to develop thermal response models for energetic materials, implement them in ALE3D, validate them with sub-scale test data, and predict the hazard response of complex, integrated munition systems. Models will include thermally-induced damage, auto-ignition, flame-spread and deflagration in thermally-damaged energetic materials, and the effects of confinement response.

The specific focus of this task will be to develop pressure-based kinetic and deflagration models for HPP based on thermochemical characterization experiments. The hot embedded fragment in rocket motor modeling will be a metric of success for this work. Scaled thermal explosion experiment (STEX) and one dimensional time to explosion (isothermal) experiments (ODTX) modeling with spirally-developed explosives kinetic and convective burn models, as well as with new fracture model capabilities, will continue to be validated with experimental data.

### *Task 4: Thermal response experiments (TRL-2/3)*

The objective of this task is to perform thermal response experiments on energetic materials, as part of developing new and validating existing thermal response models. These experiments focus on the kinetics, deflagration of intact and damaged materials, and confinement response/damage.

The specific focus of this task will be to characterize the thermochemical properties of HPP. Differential scanning calorimetry (DSC), diamond anvil cell (DAC) pyrolysis, thermogravimetric analysis (TGA), and ODTX will provide necessary data for pressure-dependent kinetics model development. High pressure strand burner (HPSB), in conjunction with porosity and permeability data, will provide necessary data for level-set deflagration model. State-of-the-art thermal explosion imaging tests will continue to provide necessary data to validate convective burn models for high-explosives and other energetic materials.

## **Summary of Current Year Results- Tasks 1 and 2**

*High performance propellant (HPP) rocket motor (RM) and burn-to-violent reaction (BVR) simulations with the propellant energetic response to mechanical stimuli (PERMS) model*

The development of predictive propellant impact response models is important for JMP, RMWIM, and the US-UK PA. AMRDEC has conducted several full-scale HPP RM experiments and plans to conduct an extensive suite of BVR experiments. The BVR experiments are important for investigating the in-bore ignition and burning of HPP, providing a basis for the development and validation of advanced propellant models. In support of previous and future AMRDEC experiments, LLNL is conducting simulations using the PERMS reactive flow model in the sub-scale BVR and the full-scale HPP RM geometries. BVR simulations have been

performed both to determine the sensitivity to PERMS model parameters (fixed geometry) and to determine peak strains in front/back plates as a function of  $\frac{3}{4}$  inch spherical projectile velocity.

The sensitivity studies show significant dependence on the projectile diameter, velocity, and their combination that accounts for 91% of the time variation of the AP burning reaction and 66% of the time variation of the aluminum after-burn. The fragment burn prefactor in conjunction with the projectile velocity and, separately, diameter accounts for another 6% of the time variation of the AP burning reaction. The aluminum burn prefactor either by itself or in conjunction with projectile velocity, projectile diameter, or fragment burn prefactor accounts for 19% of the time variation of the aluminum after-burn. The pre-BVR testing simulations show that predicted strain in the front plate far exceeds that of the back plate at most velocities, and in the front plate the strains increase with radial distance from initial projectile trajectory. The coupled BVR testing and modeling approach will provide the primary mechanism for developing new ignition and combustion models for HPP.

#### *Convective burn multiphase modeling*

The objective of this task is to develop a model for the damage, ignition, combustion, and flame-spread in thermally- and mechanically-damaged energetic materials that takes full advantage of the multi-physics (hydro-thermal-chemical) and multiphase (multi-velocity and drag, multi-temperature) capabilities in ALE3D. Predictive convective burn models are essential for assessing the explosive violence associated with unplanned mechanical and thermal stimuli.

The primary focus in FY09 has been the verification and validation (V&V) of the convective burn model for HMX-based explosives, which was released in ALE3D v4.10 recently. V&V consisted of single element simulations, 20 element linear burn (276 scenarios) simulations, and simulations of the PBX-9501 thermal explosion experiments recently conducted at LLNL. The latter simulations demonstrated the influence of the effective damaged particle size (200-600 microns) on the ignition front velocity and pressure for a fixed porosity (8%). The porosity was based on the volume change that HMX-based explosives undergo during the beta-delta phase transition. As the effective damaged particle size decreases, the ignition front velocity and pressurization rate increases. The best agreement with the PBX-9501 thermal explosion experiments came with particle sizes between 400-500 microns, which yielded a ignition front speed of 125-175 m/s and 0.8-1.1 GPa pressure. In FY10, the convective burn model will be adapted for a AP/Al/HTPB propellant (hazard class 1.3) and the non-prompt ignition model will be integrated in the framework.

#### *High explosive violent reaction (HEVR) modeling*

Most explosives and propellants, when subjected to a mechanical insult such as a drop or impact that is well below the threshold for detonation, have been observed to react. In some circumstances the reaction can be violent. The insult may be accidental (Hazards), or part of the suite of standardized tests used to assess whether the system can be designated an Insensitive Munition (IM). When specific to explosives, this behavior is known as High Explosive Violent Response (HEVR). The objective of this task is to develop a continuum-scale model that focuses on the impact-induced damage, ignition, and burning of high explosives. This model is being developed in concert with UK/AWE. Fundamental to our model is the observation that the mechanical insult produces damage in a volume of the explosive near the trajectory of the

impactor. The damage is manifest as surface area through the creation of cracks and fragments, and also as porosity through the separation of crack faces and isolation of the fragments. Once ignition occurs, open porosity permits a flame to spread easily and so ignite the newly formed surface area. The additional surface area leads to a direct increase in the mass-burning rate. As the kinetic energy and power of the insult increases, the degree of damage and the volume of damage both increase. As more energetic material is involved in the response, the pressure rises at an accelerated rate until neither mechanical strength nor inertial confinement can successfully contain the pressure. The confining structure begins to expand. This reduces the pressure and may even extinguish the flame. Both the mass of explosive involved and the rate at which the gas is produced contribute to each of several different measures of violence. Such measures include damage to the confinement, the velocity and fragment size distributions from what was the confinement, and air blast.

Our preliminary model assumes ignition happens in one or more computational zones, the ignition wave propagates with constant velocity through the damaged material surrounding the ignition zone, and the specific surface area and porosity varies throughout the volume. In our first applications of the model, the entire volume of the energetic material has been given uniform surface area and porosity. Once burning begins, the equation of state of the hot gas products is described by a tabular equation of state developed with Cheetah calculations. The cold solid is described by the same JWL equation of state used for the reactant in reactive flow models and the crushing of porosity is resisted by the cold matrix, which is described with a compaction model. The effect of changing various parameters in the model are detailed in the 2008 Annual Report. This model is currently being implemented in ALE3D, with V&V to follow shortly thereafter.

#### *FIRE modeling*

The objective of this task is to provide ALE3D modeling support to LANL on the fragment-induced and booster-induced shock initiation of PBXN-9. For the fragment-induced initiation, LANL requested fragment velocity thresholds for both 1/4 and 1/8 inch front plates. For the booster-induced initiation, LANL requested the attenuator and front plate thickness required for detonation. PBXN-9 Ignition & Growth reactive flow model parameterizations were determined based on historical pop-plot data (Montesi et al. 1995) and recent LANL data (Mas et al. 2008). The latter data suggests that PBXN-9 is more sensitive than initially believed. The geometry of the main charge and casing were identical for the two drive types and was documented in the 2008 Annual Report.

Several ALE3D simulations were performed varying the fragment velocity (1.6 to 1.9 km/s), brass attenuator thickness (1-3 mm), front plate thickness (1/4 and 1/8 inch), and the potting layer thickness between the explosive and front plate (100-200 micron based on LANL input). The fragment velocity threshold was determined to be 1.9 km/s for the 1/4 inch plate and 1.6 km/s for the 1/8 inch plate. These two-dimensional, axisymmetric simulations (intrinsically) assumed no projectile pitch. For the booster-induced initiation, it was determined that the 1/4 inch steel plate and the 200 micron potting layer sufficiently attenuates the shock impulse delivered by the PBX-9501 booster such that no attenuator is necessary. Since the potting layer is difficult to control in actual experiments, it is recommended that the worse-case thickness be used in simulations so that conservative predictions of detonation are maintained.

ALE3D simulations of the BVR experiment were performed in an effort to validate the PERMS model. While the ALE3D model captured experimental trends, inconsistency in the test data motivated further sensitivity studies. Sensitivity studies revealed that the projectile size and velocity primarily drive the propellant reaction rates. The fragmentation burn prefactor and the aluminum after-burn prefactor have an important, but secondary, influence on the reaction rates. Future studies include ALE3D modeling of a candidate rocket motor system.

#### *Diagnostic support of full-scale HPP RM experiments*

Photonic doppler velocimetry (PDV) diagnostics support was provided to AMRDEC for the full-scale HPP RM testing in early 2009 and will be provided for planned BVR testing. PDV diagnostics were used for measuring the case velocity of the rocket motor during bullet/fragment impact testing, providing a comparison metric for model predictions. The PDV data from the HPP RM tests has been distributed via the JMP website. For the planned BVR testing, PDV will be used to measure the cover plate velocity and possibly the propellant slab velocity in one-sided tests. The long-term plan is to transition PDV diagnostic capability to AMRDEC.

## **Summary of Current Year Results- Task 3 and 4**

#### *Cookoff modeling*

Predictions of the violence of confined explosions in thermal cookoff events are important to ensure the safe handling of energetic materials. Accurate predictions require codes that properly incorporate thermal transport, chemical decomposition, and mechanical deformation. In a typical cookoff process, thermal transport is required transfer heat from an external source to the energetic material. When the energetic material becomes hot enough, the material undergoes chemical transitions to different species while releasing or absorbing heat. Each species contains a unique equation of state that contributes to the total stress of the chemical mixture. This change in stress distribution causes mechanical deformation of the explosive assembly.

One experimental means to investigate the violence of thermal cookoff explosions is the Scaled Thermal Explosion Experiment (STEX). The STEX experimental apparatus features a 2" diameter by 8" long cylindrical void that is filled with a high explosive. In this study, we model a specific STEX experiment, TE-47. TE-47 featured LX-10 (95% HMX, 5% Viton A). Several code and model modifications allow for better predictions of mechanical strain than in the previous study. In particular, three efforts were focused on reducing the applied mechanical strain due to gas production by HE decomposition inside the vessel. First, an HE porosity model was implemented into ALE3D that reduced the pressure by the solid HE upon the vessel walls during the early heating stage. Second, the equation of state for the HMX intermediate and final gas products were calculated using their theoretical equilibrium chemical compositions, which results in a lower applied pressure for a large relative volume compared to ambient conditions. Third, the chemical kinetics were adjusted from previously described results to delay gas production for consistency with the small-scale thermal cookoff experiments ODTX, DSC, and TGA. The TE-47 STEX model was simulated up to a wall clock time of approximately 12 hours on 1 processor. The simulated surface temperature at thermal runaway is 182.7°C, which agrees well with the experimental temperature of 182.3°C. This error of 0.4°C is consistent with the good agreement obtained for earlier models of LX-04, LX-10, C-4 and PBXN-109. The previous



model did not contain the distinct endotherm since the first-order Arrhenius reaction progressed more slowly in the older kinetic model. Figure 7 also shows the simulated-experimental agreement of the outer thermocouple located on the outside of the AerMet 100 cylinder at  $z = 0$ . Future modeling improvements will include the linking of porosity determined via kinetic laws to level-set deflagration feature and the addition of numerical derivatives for solving the equation of state at discontinuities.

#### *Thermal explosion x-ray imaging experiments*

The objective of this project was to design and develop a capability at LLNL's HYDRA flash x-ray for imaging the deflagration front in thermal explosions. This capability is important for investigating the speed and morphology of the deflagration front in thermally-degraded materials and provides the basis for improving and validating convective burn models. LANL's proton radiography at LANSCE is the only other facility in the world that has conducted these types of experiments in the past.

The ability of HYDRA to perform the desired imaging was conclusively demonstrated in these initial experiments. X-ray imaging provided important new insights into the thermal explosion process for PBX-9501. There are several unique aspects of HYDRA: Multi-view imaging of thermal explosion to allow three-dimensional reconstruction of thermal explosion volume; Larger field of view and potential for more average images/shot; and improved access reduces experimental costs. In performing these experiments, several key component technologies were demonstrated as well: Successful use of thermocouple triggering for microsecond timing of flash x-ray system; and successful demonstration of long-term stability of charged capacitors for x-ray imaging; enables experimentally-driven triggering of imaging system (as opposed to external triggering by a detonator), even for energetic materials that have large unknowns associated with initiation mechanisms. Future testing will include diagnostics capable of measuring pressure, case expansion velocity (PDV), and temperature which will eventually improve the convective burn model.

#### *PBXN-9 fast cookoff and damaged deflagration rate experiments*

Thermal experiments of PBXN-9 were undertaken in order to understand the dynamic response of the material to thermal insult. Pressure dependent deflagration rate studies were performed at ambient temperature over a wide range of pressures and elevated temperatures over a limited pressure range. These deflagration rate studies are used to parameterize reaction and level-set deflagration models. Scaled thermal explosion experiments (STEX) consisted of fast and slow cookoff explosions for  $\delta$ -phase HMX (in PBXN-9) and slow cookoff explosion for  $\beta$ -phase HMX (in PBXN-9). Results of these STEX experiments are summarized here and compared to LX-10 studies completed previously. The STEX experiment was designed to serve as an integrated validation of the ALE3D multi-physics model.

The pressure dependent deflagration rate of PBXN-9 was determined by burning a pressed-pellet-strand of PBXN-9 at various pressures and monitoring the pressure and burn rate simultaneously. Preliminary studies of PBXN-9 were undertaken previously and completed in this fiscal year. The burn rates for PBXN-9 at various pressures were fit to the Vieille equation ( $B = aP^n$  where  $B$  is the burning rate,  $P$  is the pressure, and 'a' and 'n' are empirically derived

variables). Most notable about the pressure dependent deflagration of PBXN-9 is that the material burns in a laminar fashion over the full pressure range studied. This is in contrast to other HMX materials with similar weight percent HMX, e.g. LX-07 (90% HMX, 10% Viton A), LX-10 (95% HMX, 5% Viton A), PBX-9501 (95% HMX, 2.5% estane, 2.5% BDNPA/F), which deconsolidate and burn convectively at the higher pressures (i.e. above 100 MPa). The PBXN-9 results are particularly helpful in narrowing down the variables most affect the laminar vs. convective burn behavior. The controlling variables include material mechanical properties, and explosive-particle coating thickness (which is quantified by volume percent binder and the particle sizes). Binder reactivity cannot be ruled out as a possible variable. Preliminary studies of the pressure dependent deflagration rate of thermally damaged/hot PBXN-9 were performed. Previous work on LX-04 indicates that heating the explosive to a temperature above the  $\beta$ - $\delta$  phase transition temperature results in a significantly accelerated deflagration rate, which is most likely convective in nature. Only one heated deflagration rate study has been completed thus far; PBXN-9 was heated to 184 °C (heating rate ca. 1°C/min) and thermal soaked for 2 hours prior to deflagration initiation. The results demonstrate a significant increase in deflagration rate relative to the ambient temperature burns. Further work is necessary for the heated burn study on PBXN-9 as we are concerned that the rubber encapsulation used in the experiment may be affecting the deflagration of the material.

The final of three PBXN-9 STEX was a  $\delta$ -phase (large gap) with a heating rate of 15-30 °C/min. Temperature at explosion was 275°C and the photonic doppler velocimetry (PDV) diagnostic measured an average (over three probes) case velocity of 128 m/s. As observed in LX-10, the temperature at explosion for fast STEX far exceeds that of the slow STEX. For the slow PBXN-9 STEX, the temperature at explosion was 169-174°C. The LX-10 explosions had much higher wall velocities compared with the PBXN-9 explosions. Since violence correlates with the number and size of fragments (more and small fragments indicate a more violent explosion), it is clear that PBXN-9 is considerably less violent than LX-10 during a thermal explosion. In the post-explosion clean-up, workers noted a significant amount of undecomposed PBXN-9 spattered around the tank – indicating that the explosive was not completely consumed up to or after ignition. In conjunction with the minimal case damage, this suggests that the PBXN-9 STEX may have resulted in pressure burst, i.e., once the STEX vessel ruptured, the reaction was effectively quenched. At this time, no more STEX experiments are planned for energetic materials under this project.

#### *PBXN-9 thermal damage characterization experiments*

Thermal incidents may expose energetic materials to unexpected heat that may damage the explosive charge (e.g., change microstructure, introduce voids and porosity, and increase surface area). This may affect material properties, sensitivity, safety, and performance of the energetic materials. Reusing the damaged explosives requires a thorough analysis of the materials. In general, HMX-based formulations experienced an irreversible volume expansion and porosity increase significantly after thermal damage at temperature above 170 °C. Both burn rates and gas permeabilities of the damaged samples increased by several orders of magnitude due to higher porosity and lower density.

The thermal damage of PBXN-9 was induced by heating pressed and prill samples for 3 hours at 180 °C in an unconfined/isobaric environment. The samples were then cooled to room temperatures and characterized. In general, the samples expanded, lost weight, changed color,

and formed cracks, resulting in lower density, greater porosity and permeability. All these changes are attributed to the thermal exposure. Microscope and scanning electron microscope (SEM) images of the samples before and after thermal exposure were taken. Both post-exposure images show formation of cracks which are 10's to 100's of microns long and attributed to thermal damage. Pre and post-exposure measurements of the sample weight, volume and porosity were performed according to published procedures and are reported in 2008 Annual Report. The increase in volume is attributed to the  $\beta \rightarrow \delta$  phase transition, which is reversible but induces irreversible damage to the pressed parts. Similar observation was made on LX-10. The sample weight loss is attributed to decomposition/evaporation of the plasticizer, DOA. Thermogravimetric results of the binder + plasticizer (i.e. Hytemp + DOA) under similar thermal conditions indicate that a significant percent of the DOA evaporates after 3 hours at 180 °C. The large increase in porosity is attributed to both the damage induced by the  $\beta \rightarrow \delta$  phase transition and the loss of material due to decomposition/evaporation of DOA. Future studies investigating the effects of porosity/permeability on flame spread and combustion are important for enhancing the multi-physics/multiphase convective burn model.

#### *HPP small-scale safety testing*

The chemical reactivity test, drop hammer test, electrostatic spark test, friction test, DSC, and thermal diffusivity test were performed and HPP was qualified for use at LLNL for 10 years. TGA, ODTX, and strand burner tests are planned for FY10.

## FY10-14 Milestones and Deliverables

(focus on FY10 with details and provide general thru FY14)

Task	FY10	FY11	FY12	FY13	FY14
Task 1: Impact response modeling	Integrated simulations of key AMRDEC HPP and LANL FIRE tests				
	<ul style="list-style-type: none"> <li>1.1 Mesoscale modeling of in-bore HPP phenomenon</li> <li>1.2 Spiral 1 HPP multiphase convective burn model</li> </ul>	<ul style="list-style-type: none"> <li>1.3 HPP recompression ignition model</li> <li>1.4 Spiral 2 HPP convective burn model</li> </ul>	<ul style="list-style-type: none"> <li>1.5 Spiral 2 thermally-damaged HE SDT model</li> </ul>	<ul style="list-style-type: none"> <li>1.6 Impact of heated munition</li> </ul>	<ul style="list-style-type: none"> <li>1.7 Sympathetic response multiple heated munitions</li> </ul>
Task 2: Impact response experiments	<ul style="list-style-type: none"> <li>2.1 HPP debris cloud (1-sided BVR) tests</li> <li>2.2 BVR diagnostics support</li> </ul>	<ul style="list-style-type: none"> <li>2.3 HPP recompaction tests</li> </ul>	<ul style="list-style-type: none"> <li>2.4 Advanced non-prompt ignition tests</li> </ul>	<ul style="list-style-type: none"> <li>2.5 Advanced impact damage tests</li> </ul>	
Task 3: Thermal response modeling	<ul style="list-style-type: none"> <li>3.1 Spiral 1 HPP kinetics model</li> <li>3.2 STEX modeling with frag/venting using level-set</li> </ul>	<ul style="list-style-type: none"> <li>3.3 Spiral 2 HPP kinetics model</li> <li>3.4 STEX modeling with convective burn and frag/venting</li> </ul>	<ul style="list-style-type: none"> <li>3.5 HPP slow-cookoff modeling</li> </ul>	<ul style="list-style-type: none"> <li>3.6 Advanced kinetic models</li> </ul>	<ul style="list-style-type: none"> <li>3.7 Advanced burn models</li> </ul>
Task 4: Thermal response experiments	<ul style="list-style-type: none"> <li>4.1 HPP burn rates/thermal characteriz.</li> <li>4.2 Thermal explosion imaging tests</li> </ul>	<ul style="list-style-type: none"> <li>4.3 HPP damaged burn rates</li> <li>4.4 Friability testing of HPP</li> </ul>	<ul style="list-style-type: none"> <li>4.5 High-pressure DSC and DAC tests</li> </ul>	<ul style="list-style-type: none"> <li>4.6 Advanced burn rate tests</li> </ul>	<ul style="list-style-type: none"> <li>4.7 Advanced thermal explosion imaging tests</li> </ul>

## Transition Plan

The primary means of technology transfer to DoD collaborators is through the vehicle of ALE3D and energetic material models therein. For this project, this means creating models of physical and chemical phenomena relevant to problems of mutual interest, which in this case is assessing safety hazards of existing systems and evaluating system options for meeting IM requirements for future systems, and providing technical support to those in DoD who are applying these models. Transitions are also being made in the area of advanced test diagnostics.

This project is actively engaging the tri-service laboratories:

- Collaborating with AMRDEC on the ALE3D modeling of the HPP RM and BVR experiments, including the development on in-bore ignition and convective burning models; Also providing PDV diagnostic support to HPP RM and BVR experiments
- Collaborating with AFRL/Munitions on the shock initiation testing and SDT reactive flow model parameterization of PBXN-112 and AFX-757
- Collaborating with Edwards AFB on the ALE3D modeling of the cookoff response of large diameter rocket motors
- Collaborating with Army SMDC on the ALE3D modeling of laser-initiation and fast cookoff of TNT-filled mortar rounds
- Collaborating with ARDEC on the ALE3D modeling of slow and fast cookoff of HMX-based explosives

## Issues

One area of significant technical risk is the development of models for in-bore ignition of HPP. This requires fundamental understanding of the ejecta damage, compressive ignition, and burning of damaged propellant. Initial testing at AMRDEC will explore this phenomenon and lead to more focused testing at AMRDEC and LLNL for the purpose of developing predictive modeling capabilities. To account for the apparent lack of repeatability in these types of tests, these models should possess a stochastic component. This component would ultimately reflect the heterogeneity of the energetic material at the meso-scale.

The departure of kinetic model developer, Aaron Wemhoff, presented a challenge. Libby Glascoe is now the main kinetic model developer on this project.

Late HPP delivery has delayed LLNL characterization and modeling efforts. We are ramping up efforts to minimize the effects of these delays.

## Publications, Presentations, References

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